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THE EFFECT OF CLOUDINESS ON A GREENHOUSE MODEL OF THE VENUS ATMOSPHERE

GEORGE OHRING JOSEPH MARIANO

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Abstract. In previous models of the greenhouse effect in the Venus atmosphere, it has been assumed that infrared-absorbing atmospheric gases provide the sole contribution to the infrared opacity of the Venus atmosphere. In the present study, the influence of an extensive cloud-cover, opaque to infrared radiation, is also included in the greenhouse model. The magnitude of the greenhouse effect, which is defined here as the ratio of the surface temperature produced by the greenhouse to the surface temperature of an atmosphere-less Venus, is computed as a function of infrared opacity of the atmosphere, and amount and height (actually ratio of cloud-top pressure to surface pressure) of clouds. It is assumed that the Venus atmosphere is grey, the absorbing gas has a constant mixing ratio, and the temperature variation with altitude is linear. Calculations are made for two temperature lapse rates: the adiabatic lapse rate, and nine-tenths of the adiabatic lapse rate. The adiabatic lapse rate maximizes the greenhouse effect; for this case estimates of the minimum infrared opacity required to maintain the observed surface temperature can be determined. For a surface temperature of 700K, 99% cloudiness, and cloud-top temperature of 240K, the minimum required infrared opacity is six. Uncertainties and questionable side effects of the model are discussed.

Introduction. One of the most surprising results in the field of observational astronomy has been the recent finding that the surface temperature of Venus is remarkably high--about 600K to 700K. The indications of high surface temperature are based upon observations from the earth of the planet's emission of microwave radiation (see Roberts, 1963 for a summary of these observations); these indications have recently been confirmed by the microwave radiometer measurements made by the Mariner spacecraft on its Venus fly-by (Barath, et al., 1963). The reason that these temperatures are considered remarkable is that they are two to three times the temperature that Venus was expected to have, based upon its distance from the sun and its planetary albedo. This discrepancy between what was expected and what was observed has stimulated a good deal of research to explain the cause of the high temperatures.

One means by which the surface temperature of a planet can be kept high is the greenhouse mechanism. In order for this mechanism to be effective the atmosphere must be relatively transparent to incoming solar radiation and relatively opaque to outgoing infrared radiation. In previous models of the greenhouse mechanism, the effect of the extensive Venusian cloud cover on the transfer of infrared radiation has not been directly considered. In the present study the effect of a cloud cover, opaque to infrared radiation, on a greenhouse model of the Venusian atmosphere is investigated.

Background. A large greenhouse effect as an explanation of the high surface temperature of Venus was first suggested by Sagan (1960). He used the following equation for the balance of incoming solar and outgoing infrared radiation at the top of the Venus atmosphere:

$$\sigma T_e^4 = \sigma T_a^4 + t \sigma T_g^4 \qquad (1)$$

where σ is the Stefan-Boltzmann constant, T_e is the effective temperature of the incoming solar radiation (allowing for albedo losses), T_a is the effective radiating temperature of the atmosphere, T_g is the planetary surface temperature, and t is the transmissivity of the atmosphere for infrared radiation. The left side of the equation represents the incoming solar radiation, the right side the outgoing infrared radiation. With this equation Sagan was able to compute the atmospheric infrared transmissivity required to maintain a 600K surface temperature. Assuming T_a = 234K, he obtained a required transmissivity of about 0.9% for the case of T_e = 254K (corresponding to an albedo of 0.64), and 0.2% for the case of T_e = 240K (corresponding to an albedo of 0.71). Making use of laboratory emissivity measurements of carbon dioxide and water vapor, he found that 18 km STP of carbon dioxide together with 9 g cm^{-2} of water vapor could produce the required transmissivities. Since these amounts of gases are not incompatible with present knowledge of the Venus atmosphere, a strong greenhouse effect appears possible.

However, another theoretical attack on the problem, by Jastrow and Rasool (1962), with a different approach led to a different conclusion. Making use of the Eddington approximation to compute the radiative equilibrium temperature distribution in the atmosphere of Venus, they found that the required infrared transmissivities for a 600K temperature were so small as to be incompatible with present knowledge of the composition of the Venus atmosphere. For a grey atmosphere in radiative equilibrium the Eddington approximation leads to the following formula for surface temperature:

$$T_g = T_e \; (1 + 0.75 \; \tau_g)^{\frac{1}{4}} \tag{2}$$

where τ_g is the atmospheric opacity in the infrared. For a T_e value of 254K the required opacity is about 40, and for a T_e value of 234K the required opacity is about 30. These opacities correspond to transmissivities less than 10^{-22}, or many orders of magnitude less than those required in Sagan's model. The essential cause of the difference between the two models is due to Sagan's choice of 234K for T_a; the required transmissivity depends critically upon the value of T_a, which is really unknown and must be assumed.

The effect of cloud cover on the infrared radiation leaving the planet has not been specifically included in the previous two approaches. The amount of cloud cover in the Venus atmosphere is large, and if the cloud cover acts as a blackbody for infrared radiation, as the water clouds of the earth's atmosphere do, it should enhance the greenhouse effect. In the model discussed below the effect of cloudiness is included.

Model. It is assumed that Venus has a grey atmosphere with an extensive cloud cover that is opaque to infrared radiation. For totally clear skies the outgoing flux of infrared radiation from a grey atmosphere can be written as (see, for example, Elsasser, 1942)

$$F(o)_{clear} = 2E_3(\tau_g)B_g + \int_o^{\tau_g} B(\tau)\ E_2(\tau)\ d\tau \tag{3}$$

where E is the exponential integral, τ is the infrared opacity, B is the blackbody flux, and the subscript g refers to the planet's surface. The first term on the right represents the contribution from the surface; the second the contribution from the atmosphere. The blackbody flux is related to temperature through

$$B = \sigma\ T^4 \tag{4}$$

The opacity is defined as

$$\tau = -\alpha \int_\infty^z \rho\ dz \tag{5}$$

where α is the grey absorption coefficient for the atmosphere whose density is ρ.

If there is a complete cloud cover at some level τ_c, the outgoing flux of infrared radiation can be written as

$$F(o)_{cloudy} = 2E_3\,(\tau_c)B_c + 2 \int_o^{\tau_c} B(\tau)\;E_2(\tau)\;d\tau \tag{6}$$

If only a fraction, n, of the sky is cloud covered, the outgoing radiation flux will contain contributions from both clear and cloudy parts according to

$$F(o) = (1 - n)\;F(o)_{clear} + n\;F(o)_{cloudy} \tag{7}$$

It is now assumed that the atmospheric temperature is a linear function of height; the temperature-pressure relationship can then be written as

$$\frac{T_a}{T_g} = \left(\frac{p_a}{p_g}\right)^k \tag{8}$$

With the use of Equations (4), (5), (8), and the hydrostatic equation, it can be shown that

$$\frac{B}{B_g} = \left(\frac{\tau}{\tau_g}\right)^{4k} \tag{9}$$

If the cloud top is at the level $\tau_c = p\tau_g$, Equation (7) can be written as

$$F(o) = (1 - n)\left[2E_3(\tau_g)B_g + 2B_g\tau_g^{-4k}\int_o^{\tau_g} \tau^{4k}\, E_2(\tau)d\tau\right] + n\left[2E_3(p\tau_g)p^{4k}B_g + 2B_g\tau_g^{-4k}\int_o^{p\tau_g} \tau^{4k}\, E_2(\tau)d\tau\right] \tag{10}$$

With the requirement that the outgoing infrared radiation must balance the incoming solar radiation, or

$$F(o) = \sigma\, T_e^{\,4} \tag{11}$$

and with $B_g = \sigma\, T_g^{\,4}$, one can obtain an expression relating the magnitude of the greenhouse effect to the amount of cloudiness, n, the height of the cloud-top (as represented by p), and the atmospheric infrared opacity, τ_g:

$$(T_e/T_g)^4 = (1 - n)\left[2E_3(\tau_g) + 2\tau_g^{-4k}\int_o^{\tau_g} \tau^{4k}\, E_2(\tau)d\tau\right] + n\left[2E_3(p\tau_g)p^{4k} + 2\tau_g^{-4k}\int_o^{p\tau_g} \tau^{4k}\, E_2(\tau)d\tau\right] \tag{12}$$

The ratio T_g/T_e is the ratio of the greenhouse surface temperature to the surface temperature that Venus would have without an atmosphere; this ratio represents the magnitude of the greenhouse effect.

Calculations. For a given infrared opacity, and amount and height of cloud cover, the greenhouse mechanism will lead to a maximum surface temperature when the lapse rate is at its limiting value: the adiabatic lapse rate (Ohring, 1962). Thus, if an adiabatic lapse rate is used in the computations, the greenhouse effect is maximized. Under adiabatic conditions the value of k is equal to $(\gamma - 1)/\gamma$, where γ is the ratio of the specific heat at constant pressure to the specific heat at constant volume. γ depends upon composition and, for a Venus atmosphere of 95% nitrogen and 5% carbon dioxide (Spinrad, 1962), is equal to 1.4; the value of k is then 0.286. The integrals in Equation (12) can be evaluated analytically only for values of 4k equal to integers; for non-integer values of 4k numerical methods must be used.

With the use of the recursion formulas for the exponential integrals, and the relationships

$$E'_{n+1}(\tau) = -E_n(\tau) \text{ for } n \geq 1 \text{ and } E'_1(\tau) = -e^{-\tau}/\tau,$$

and by repeated integration by parts, Equation (12) can be rewritten as

$$(T_e/T_g)^4 = (1-n)\left\{e^{-\tau_g}(1-\tau_g) + \tau_g^{\,2}\, E_1(\tau_g) + 2\tau_g^{-4k}\left[\frac{\tau_g^{4k+1}}{4k+1}\, e^{-\tau_g} - \frac{E_1(\tau_g)\,\tau_g^{4k+2}}{4k+2} + \frac{1}{(4k+1)(4k+2)}\int_o^{\tau_g} \tau^{4k+1}\, e^{-\tau} d\tau\right]\right\} +$$

$$+ n\left\{p^{4k}\left[e^{-p\tau_g}(1-p\tau_g) + (p\tau_g)^2 E_1(p\tau_g)\right] + 2\tau_g^{-4k}\left[\frac{(p\tau_g)^{4k+1}}{4k+1}\, e^{-p\tau_g} - \frac{E_1(p\tau_g)(p\tau_g)^{4k+2}}{4k+2} + \frac{1}{(4k+1)(4k+2)}\int_o^{p\tau_g} \tau^{4k+1}\, e^{-\tau} d\tau\right]\right\} \quad (13)$$

For values of the argument less than 1, the series (Chandrasekhar, 1960)

$$E_1(x) = -\gamma - \ell n\, x + \sum_{n=1}^{\infty} \frac{(-1)^{n-1}\, x^n}{n \cdot n!}, \quad (14)$$

where $\gamma = 0.5772157$, was used to evaluate the first exponential integral appearing in Equation (13). This series converges rapidly for $x \leq 1$ and the absolute magnitude of each term decreases monotonically. However, for values of x greater than 1 the absolute magnitude of successive terms no longer decreases monotonically, and the Chebyshev approximation method of Hastings (1955) was used for these values of x:

$$E_1(x) \approx \frac{e^{-x}}{x}\left[\frac{a_o + a_1 x + a_2 x^2 + a_3 x^3 + x^4}{b_o + b_1 x + b_2 x^2 + b_3 x^3 + x^4}\right] \tag{15}$$

where

$a_o = 0.2677737$ $\quad$ $b_o = 3.958497$

$a_1 = 8.634761$ $\quad$ $b_1 = 21.09965$

$a_2 = 18.05902$ $\quad$ $b_2 = 25.63296$

$a_3 = 8.573329$ $\quad$ $b_3 = 9.57332$

This approximation was found to give numerical solutions to $E_1(x)$ to at least 7 place accuracy in the interval $1 < x \leq 30$.

For the integrals appearing in Equation (13), which are of the form

$$I(x) = \int_o^x \xi^{\ell} e^{-\xi} d\xi \qquad (\ell \text{ not an integer}), \tag{16}$$

the following method was adopted. For values of $x \leq 1$ the series

$$I(x) = \sum_{m=1}^{\infty} \frac{(-1)^{m-1} x^{\ell+m}}{(\ell + m)(m - 1)!} \tag{17}$$

was used. This series is obtained by expanding $e^{-\xi}$ in a power series about the point $\xi = 0$ and integrating each term successively. For values of $x > 1$ this series becomes impractical for accurate machine computation, and Simpson's rule of integration was used for these values of x.

With the above numerical techniques the evaluation of Equation (13) reduces to that of solving a complex algebraic equation, and a computer program was written to accomplish this. Computations were performed for $k = 0.286$ (the adiabatic value), and a range of values for τ_g, p, and n. The greenhouse effect ratios (T_g/T_e) are shown graphically as a function of τ_g and p in Figures 1, 2, 3, and 4 for 0.8, 0.9, 0.95, and 0.99 cloudiness, respectively. In the model the infrared opacity above any level is proportional to the pressure at that level so that p, the ratio of the infrared opacity above the cloud-top to the infrared opacity of the entire clear part of the atmosphere, also represents the ratio of cloud-top pressure to surface pressure, and, thus, can be used as a measure of the cloud-top height. The lowest curve on each of these diagrams represents a cloud located at the surface; or, more importantly, this case can be interpreted as no cloud at all or completely clear skies; this curve serves as a reference curve for evaluating the effect of clouds, which is illustrated by the upper curves.

It is obvious from these diagrams that the magnitude of the greenhouse effect increases as the infrared opacity and amount of cloudiness increase. It is also evident that the greenhouse effect increases as the value of p decreases (or as the height of the cloud-top increases).

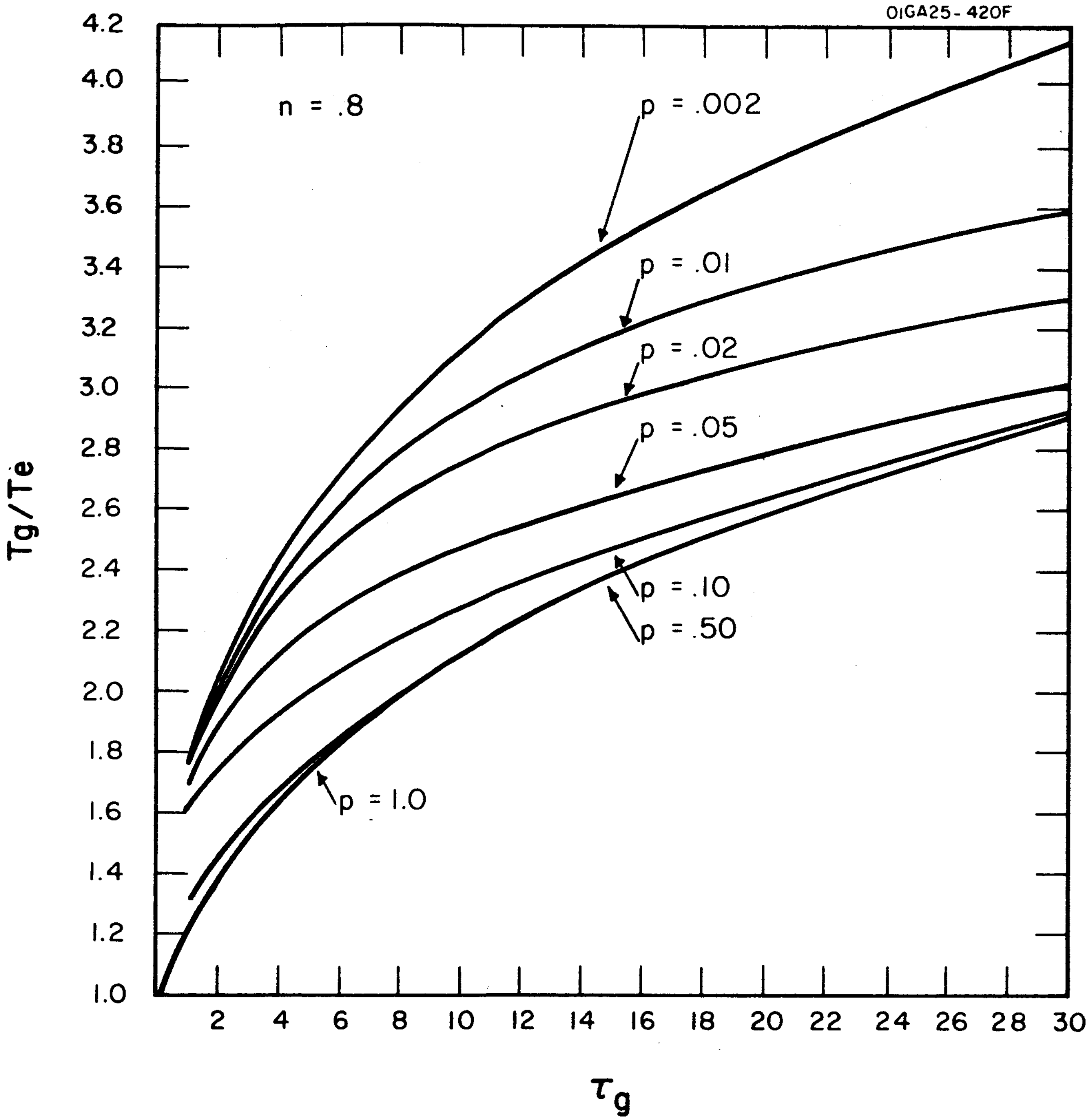

Figure 1. Magnitude of the greenhouse effect on Venus for 80% cloud cover and adiabatic lapse rate. (T_g/T_e is the ratio of the greenhouse surface temperature to the surface temperature of an atmosphere-less Venus; τ_g is the atmospheric infrared opacity; and p is the ratio of cloud-top pressure to surface pressure.)

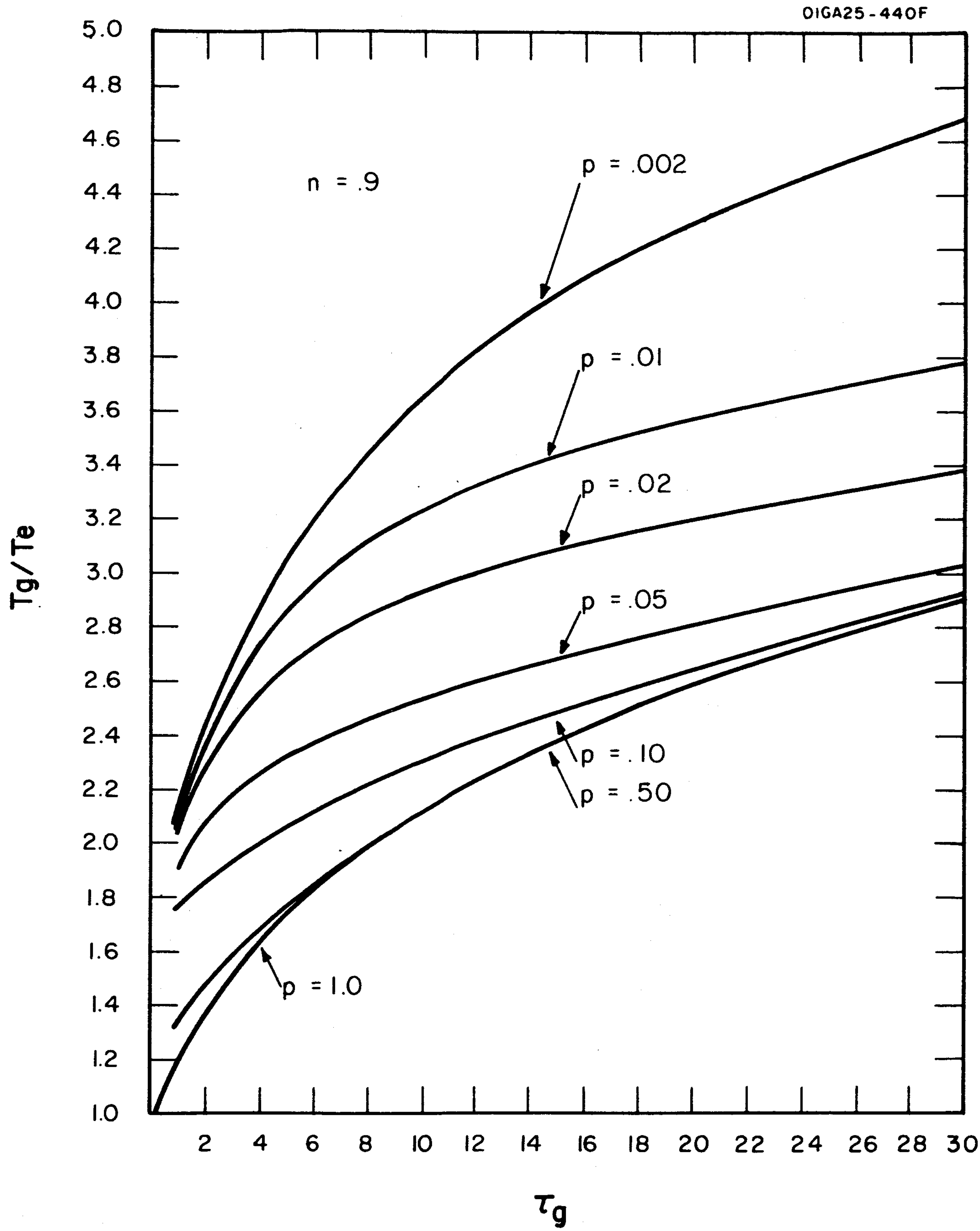

Figure 2. Magnitude of the greenhouse effect on Venus for 90% cloud cover and adiabatic lapse rate. (Symbols are defined in Figure 1 caption.)

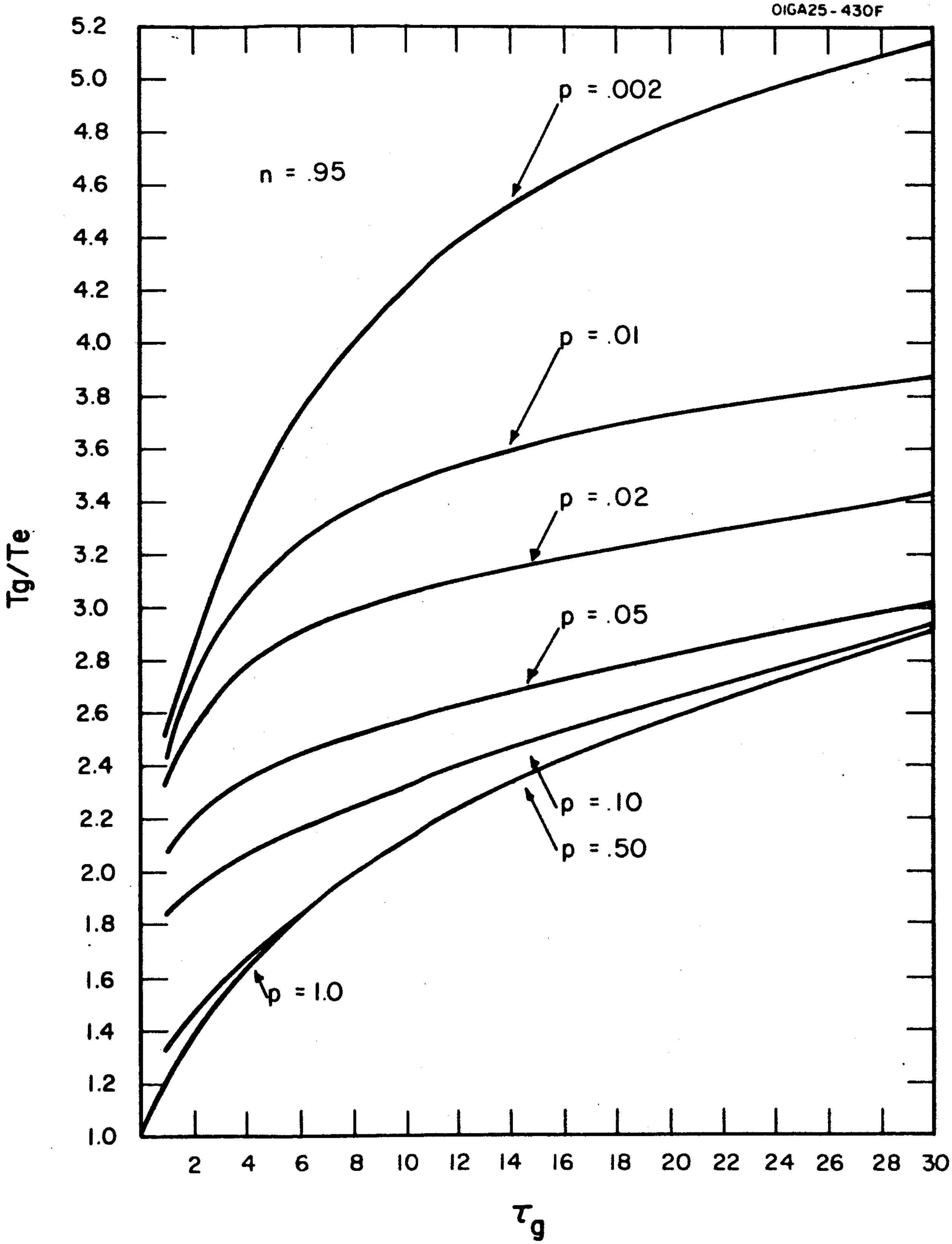

Figure 3. Magnitude of the greenhouse effect on Venus for 95% cloud cover and adiabatic lapse rate. (Symbols are defined in Figure 1 caption.)

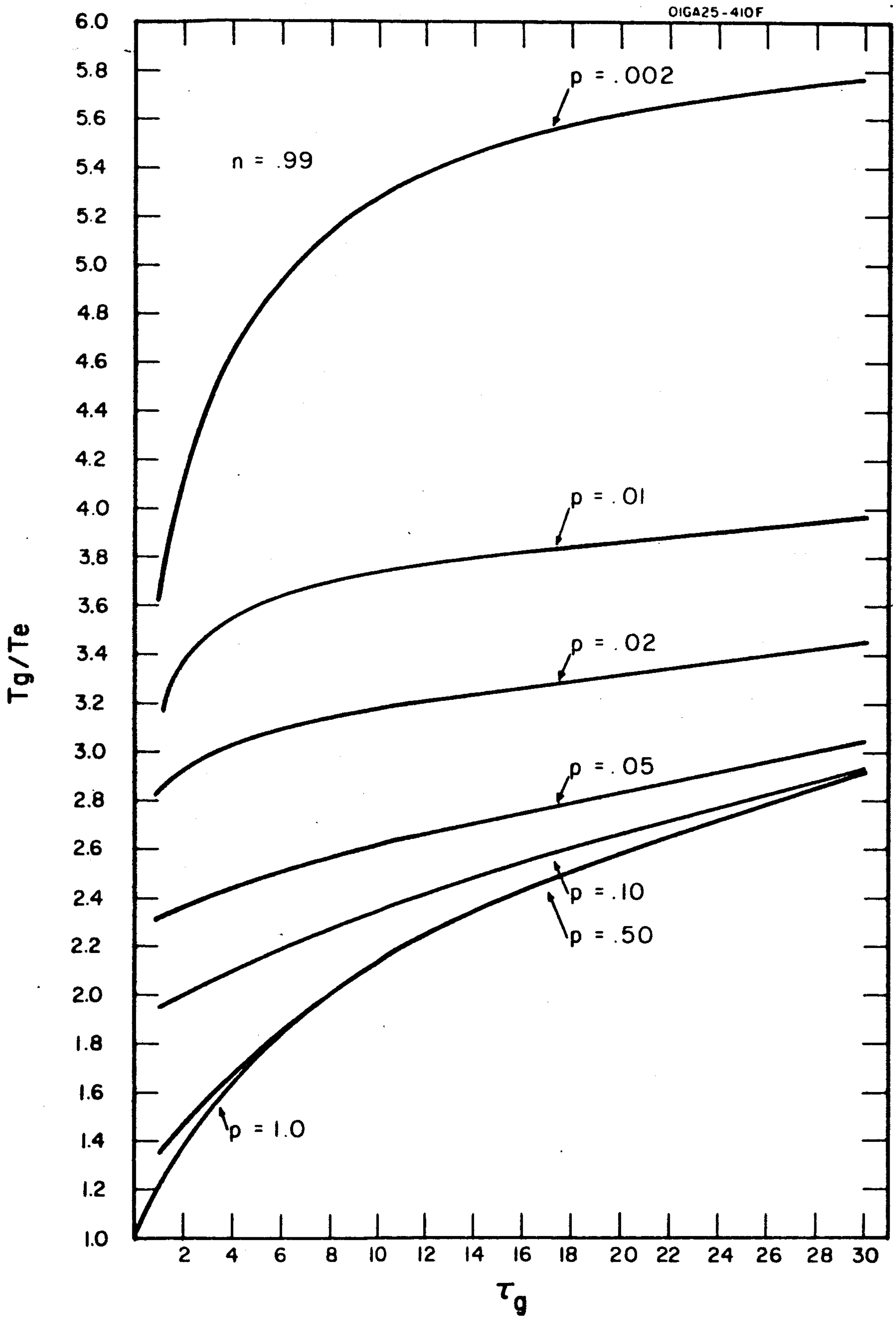

Figure 4. Magnitude of the greenhouse effect on Venus for 99% cloud cover and adiabatic lapse rate. (Symbols are defined in Figure 1 caption.)

The influence of cloudiness on the magnitude of the greenhouse effect can be seen by comparing the upper curves with the curve p = 1, which represents the greenhouse effect for the case of clear skies.

To illustrate the use of these diagrams, let us determine the infrared opacity, τ_g, required to maintain the observed surface temperature on Venus. The Mariner microwave observations (Barath et al., 1963) and the earth based microwave observations (Sagan, 1962) suggest an average surface temperature of about 700K. The effective temperature of the incoming solar radiation, T_e, is 237K, which corresponds to an albedo of 0.73 (Sinton, 1962). The magnitude of the greenhouse effect, T_g/T_e, is then 2.95. In order to determine the required infrared opacity, values for the amount and height of the clouds must be assumed. The Mariner infrared observations, which detected no breaks in the cloud layer (Chase et al., 1963) the telescopic observations, and the large visual albedo of Venus, all suggest that Venus has a very extensive cloud cover; thus, the diagram for 99% cloudiness can be used for the computation. The Mariner infrared observations also suggest a cloud temperature of about 240K. Since the temperature-pressure relationship was fixed at the adiabatic rate in these computations, p, the ratio of cloud-top pressure to surface pressure, can be inferred from the ratio of cloud-top temperature to surface temperature. For a cloud-top temperature of 240K and surface temperature of 700K, p is 0.024. The required opacity, for $T_g/T_e = 2.95$, n = 0.99, and p = 0.024, is from Figure 4, $\tau_g \approx 6$. This opacity corresponds to an infrared transmissivity of about 0.06%, which, although very low, could possibly be achieved with sufficient carbon dioxide and water vapor in the Venus atmosphere. In any event the computation indicates that the required opacity in the case of 99% cloudiness is much lower than the required opacity for totally clear skies, which, according to these diagrams, is over 30.

It should be emphasized that the above calculations were based upon an adiabatic lapse rate of temperature; this lapse rate results in a maximum possible surface temperature and, thus, the opacities computed above are actually minimum required opacities. The magnitude of the greenhouse effect can also be computed for other values of the lapse rate; computations were also made with a value of k = 0.25, which corresponds to a temperature lapse rate of about 0.9 of the adiabatic. With k = 0.25 the integrals in Equation (12) can be evaluated analytically and the resulting greenhouse equation is

$$(T_e/T_g)^4 = \frac{(1-n)}{3}\left\{2\tau_g^{-1}\left[1 - \exp(-\tau_g)\right] + 2E_3(\tau_g)\right\} + \\ + \frac{np}{3}\left\{2(p\tau_g)^{-1}\left[1 - \exp(-p\tau_g)\right] + 2E_3(p\tau_g)\right\} \tag{18}$$

Computations of the magnitude of the greenhouse effect, T_g/T_e, were performed for the same range of values of the parameters τ_g, n, and p, as in the adiabatic case; the results are shown in Figures 5, 6, 7, and 8. It is quite evident from inspection of these diagrams and comparison

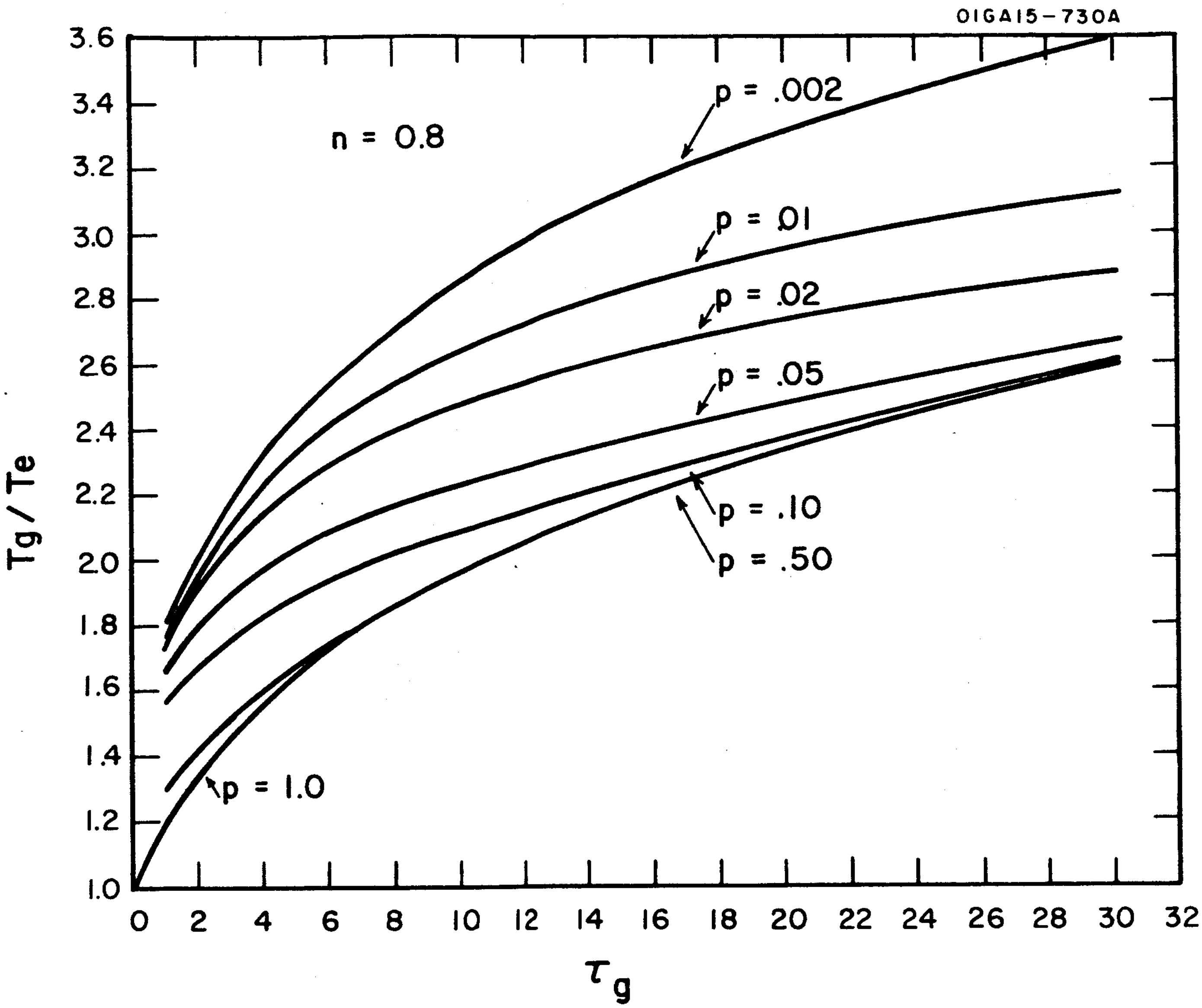

Figure 5. Magnitude of the greenhouse effect on Venus for 80% cloud cover and a temperature lapse rate of nine-tenths adiabatic. (Symbols are defined in Figure 1 caption.)

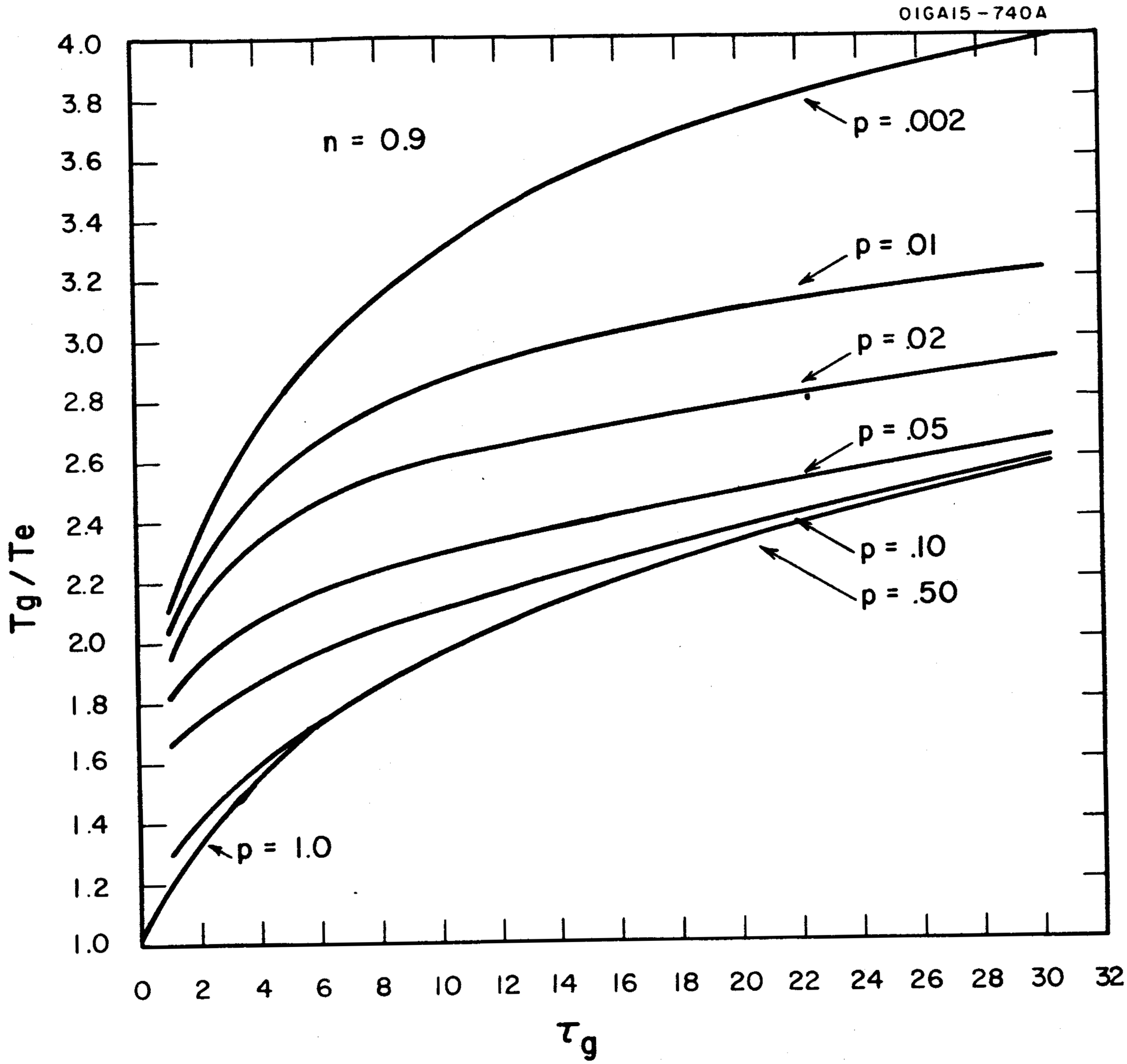

Figure 6. Magnitude of the greenhouse effect on Venus for 90% cloud cover and a temperature lapse-rate of nine-tenths adiabatic. (Symbols are defined in Figure 1 caption.)

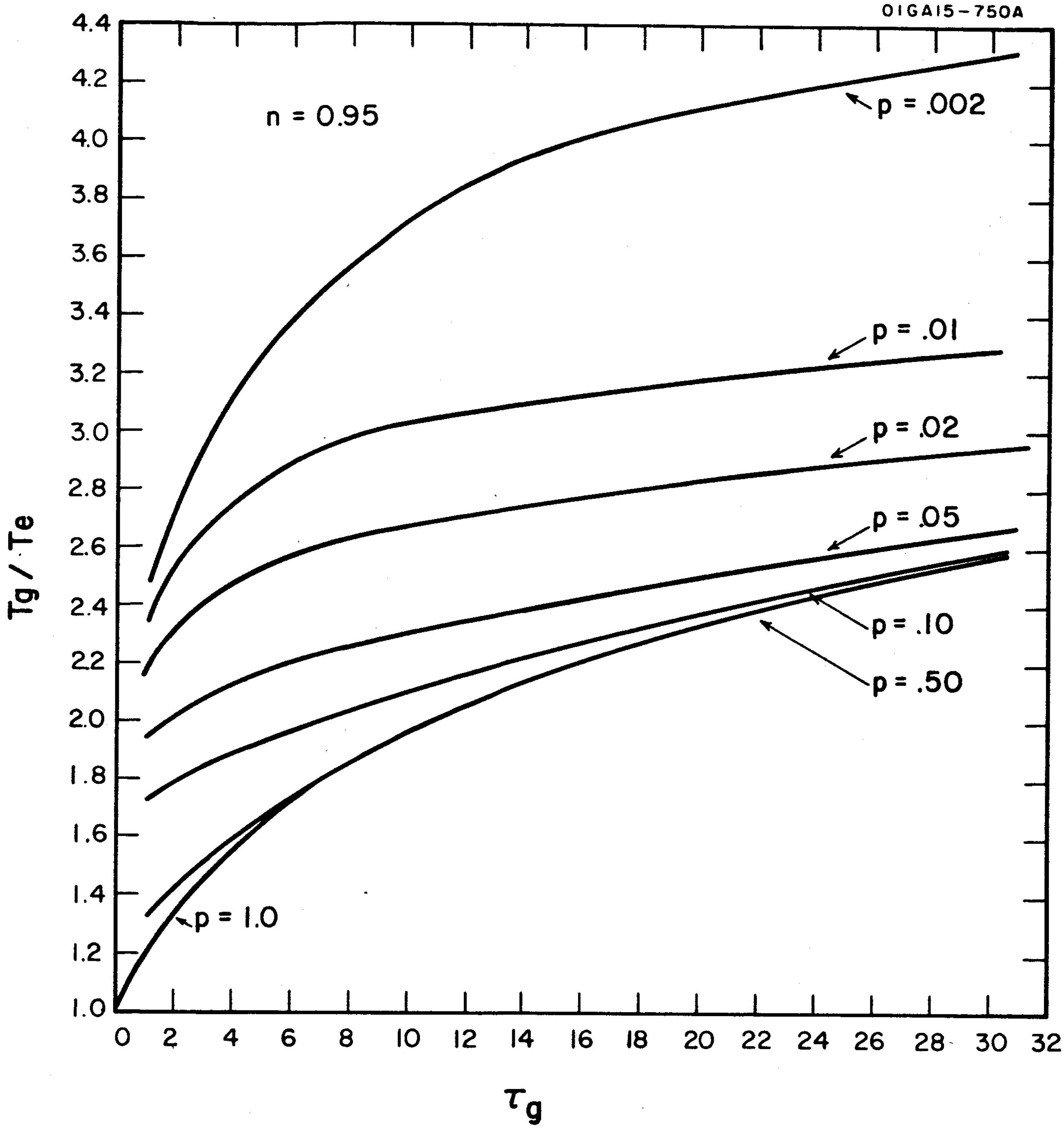

Figure 7. Magnitude of the greenhouse effect on Venus for 95% cloud cover and a temperature lapse-rate of nine-tenths adiabatic. (Symbols are defined in Figure 1 caption.)

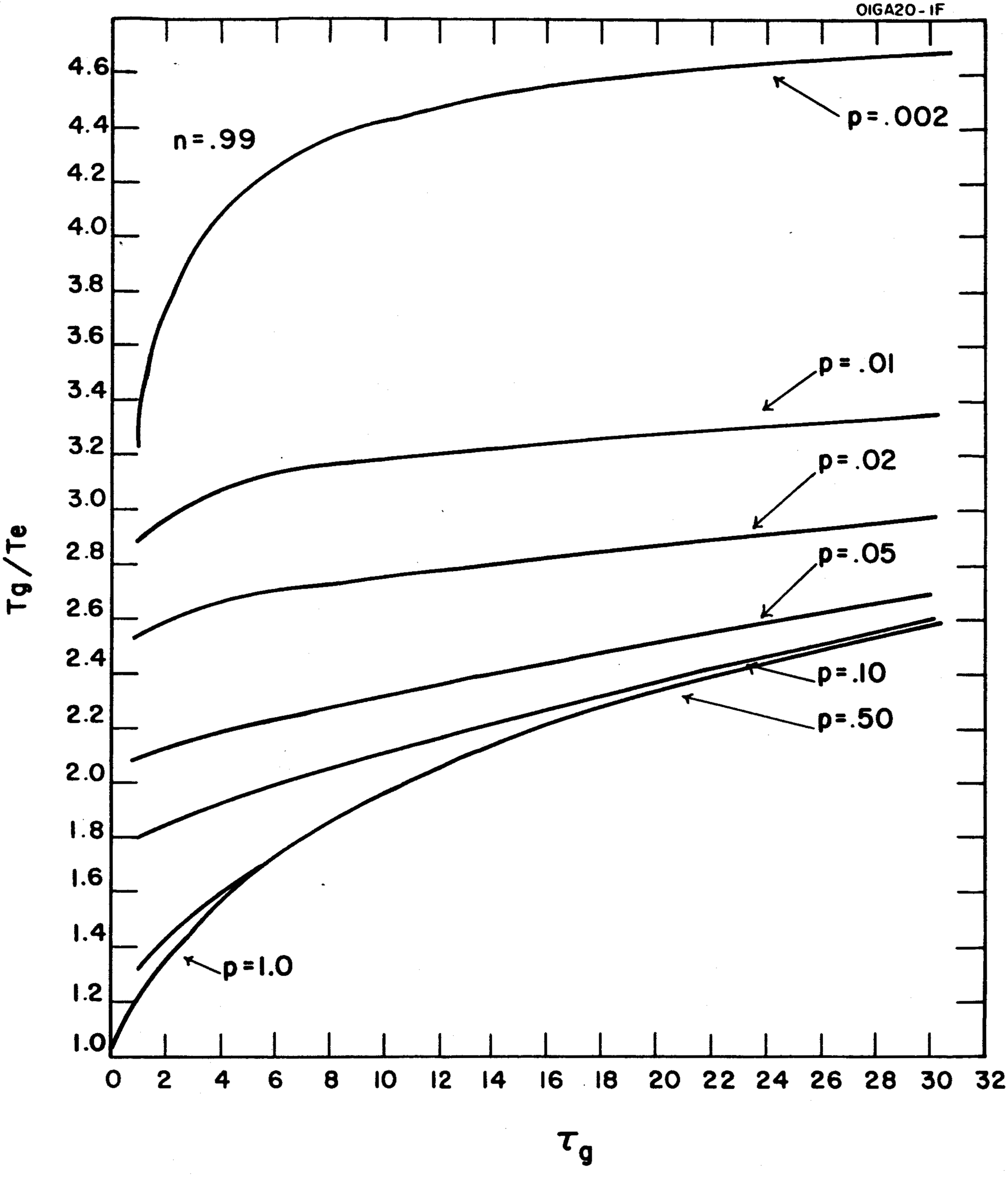

Figure 8. Magnitude of the greenhouse effect on Venus for 99% cloud cover and a temperature lapse-rate of nine-tenths adiabatic. (Symbols are defined in Figure 1 caption.)

with the previous diagrams that the magnitude of the greenhouse effect is lower than in the adiabatic case--the exact decrease depending upon τ_g, p, and n.

A sample calculation, similar to the one performed in the adiabatic case, of the infrared opacity required to satisfy the observed greenhouse effect can be performed. The value of p is different in this case since the temperature-pressure relationship is different. With a cloud-top temperature of 240K and a surface temperature of 700K, p, the ratio of cloud-top pressure to surface pressure,is now 0.014. With the magnitude of the greenhouse effect equal to 2.95, a cloud amount n = 0.99, and p = 0.014, the required infrared opacity, τ_g, from Figure 8, is about 7. This opacity corresponds to an infrared transmissivity of 0.02%, a value somewhat lower than the transmissivity of 0.06% required in the adiabatic case.

These sample calculations as well as two additional ones for a surface temperature of 600K are summarized in Table 1. As expected the required opacities for the 600K surface temperature are less than for the 700K surface temperature.

Summary and Critique. The model developed in this study is an attempt to include the influence of cloudiness on the magnitude of the greenhouse effect on Venus. For purposes of the model it is not necessary to specify the composition of the clouds; the only requirement

Table 1. Infrared opacities required to maintain observed surface temperature on Venus.

n	T_g (^oK)	(T_g/T_e)	T_{cloud} (^oK)	k	p	Required Opacity, τ_g
0.99	700	2.95	240	0.286	0.024	6
0.99	700	2.95	240	0.25	0.014	7
0.99	600	2.5	240	0.286	0.041	2.5
0.99	600	2.5	240	0.25	0.026	3

is that they be opaque to infrared radiation. The presence of such a cloud in the Venus atmosphere will enhance the greenhouse effect since, with the temperature decreasing with height, the cloud will absorb the high-temperature surface radiation and re-radiate to space at lower temperatures. Graphs are presented which enable one to determine the magnitude of the greenhouse effect for a range of infrared opacities, cloudiness amounts, cloud-top heights, and two temperature lapse-rates. Or, if the magnitude of the greenhouse effect is known, the infrared opacity required to maintain the observed surface temperature can be determined. Sample calculations, based upon current estimates of cloud-top temperature and 99% cloudiness, indicate that the minimum value of the infrared opacity required to maintain a 700K surface temperature is about 6. If the surface temperature is 600K, the minimum value of the required opacity is between 2 and 3.

A number of assumptions are made in the development of the model; to the extent that these assumptions are invalid, the final results may be in question. The assumption of a grey atmosphere is incorrect, just how much this assumption influences the final results is unknown. It is implicitly assumed that the absorbing gases are uniformly mixed with height; departures from constant mixing ratios would affect the final results. The clouds are assumed to be completely opaque to infrared radiation; any departures from complete opaqueness would certainly influence the results presented here. And last, but perhaps not least, it is implicitly assumed that there is a negligible amount of absorption of solar radiation in the atmosphere; this assumption has been made in previous Venus greenhouse models, is certainly questionable, and its effect should be evaluated in more realistic models.

The model also has questionable side-effects. This can best be seen by considering the case with a lapse rate of about nine-tenths the adiabatic rate ($k = 0.25$), in which the radiative transfer integrals can be evaluated analytically. When one computes the net flux of infrared radiation at the surface and subtracts this from the outgoing flux of infrared radiation at the top of the atmosphere, one finds that there is a flux convergence--or radiational heating of the atmosphere--if p, the ratio of cloud-top pressure to surface pressure, is less than 0.5. If some of the incoming solar radiation is absorbed directly by the atmosphere, the heating of the atmosphere by radiational processes would be increased further. The convergence of radiational energy in the atmosphere is equal to a net upward flux of radiation--considering both solar radiation and infrared radiation--at the surface. This state of affairs is contrary to what one would expect; for example, in the earth's atmosphere there is divergence of infrared radiation flux in the atmosphere, and the net flux of radiation at the surface--considering both solar and infrared radiation--is directed downward. The implication is that unless atmospheric circulation processes transport energy from atmosphere to surface on Venus--in contrast to circulation processes on the earth --the temperature distribution assumed in the model would not maintain itself. Matters are helped somewhat if one takes into consideration the fact that the cloud has a finite vertical extent. For example, with a cloud thickness of about 30 km, the critical value of p, below which an atmospheric convergence of radiation results, decreases to about 0.05. Improvements in this type of model should be aimed at eliminating or understanding these side effects.

Since the model is fairly general, it can be applied to other planets; and since there are a number of uncertainties in the model, application to other planets, specifically Mars and the Earth, where the values of the parameters are better known, provides a test of the model. Applying it to Mars, and assuming T_e = 219K (corresponding to an albedo of 0.15), no clouds, τ_g = 0.5 (after Arking, 1962), and a lapse rate of nine-tenths of the adiabatic lapse rate, one obtains a surface temperature of about 240K, in reasonable agreement with the estimate of about 230K obtained in a more elaborate treatment (Ohring, et al., 1962). Applying it to the earth, and assuming T_e = 252K (corresponding to an albedo of 0.35), 50% cloudiness, a p value of 0.5 (corresponding to an average cloud-top pressure of 500 mb), τ_g = 1.6 (corresponding to an infrared flux transmissivity of 10%, and a k value of 0.176 (corresponding to a lapse rate of 6.0K/km), one obtains a surface temperature of 3.3K, which is within 10% of the observed average surface temperature of the earth, 288K. These last calculations serve to indicate the possible uncertainties associated with the use of the model.

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